

# Implementation of National Space Policy on US Air Force End of Life Operations and Orbital Debris Mitigation

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Recent changes to US space policy regarding the execution of satellite End of Life (EOL) procedures have been driven by the rising significance of the orbital debris problem in Low Earth Orbit (LEO). Therefore current EOL plans are written largely with the aim of reducing long-lasting debris that can linger for decades in the orbit of the defunct satellite. Through an exhaustive discussion of US National, Department of Defense and Air Force Space Command policies for mitigation of orbital debris, this paper details several considerations for writing operational EOL plans, with special applicability to military missions and focus on LEO satellites that are unable to relocate to a graveyard orbit. Further, the recent ungainly re-entry of NASA's Upper Atmosphere Research Satellite (UARS) has highlighted the need to incorporate debris mitigation into the EOL plan after contact has been lost or during re-entry in the interest of public safety. In light of this incident, methods currently used by Air Force Orbital Safety professionals to assess and minimize orbital debris released during and after EOL satellite passivation by accidental explosions, by intentional breakup and due to on-orbit collisions with existing debris are discussed. As integral parts of a holistic EOL plan, re-entry survivability analysis, casualty expectation analysis and intentional breakup activities are also addressed.

## I. Introduction

THE problem of orbital debris and its obstruction to clear and easy access to space has long been an item of national and defense interest, not just in the United States but in space-faring countries around the world. All Department of Defense (DoD) and United States Air Force (USAF) regulations that ensure compliance with orbital debris minimization goals stem from the US Government (USG) Orbital Debris Mitigation Standard Practices<sup>1</sup> (ODSPs). This high-level document addresses how all American space programs should conduct their operations with the minimization of orbital debris in mind. The USG ODSPs are addressed in four general objectives:

1. Control of debris released during normal operations
2. Minimizing debris generated by Accidental Explosions
3. Selection of a safe flight profile and operational configuration
4. Post mission disposal of space structures.

This paper will touch mostly on the fourth objective, i.e., the mitigation of orbital debris at satellite End of Life (EOL) or end of mission, and the implementation of space policy currently in place on such operations. Especially at EOL, when control over the space vehicle is lost due to low altitude or given up due to end of mission activities, minimizing the risk of debris creation due to accidental explosions and maintaining a safe operational configuration are relevant concerns, and we shall address them accordingly in this paper.

The President's National Space Policy<sup>2</sup> directive (2010) recognizes the problem of orbital debris and its risk to space operations and national interests, and directly references the USG guidelines by stating that "All Departments and Agencies shall continue to follow the US Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness". The USG guidelines are therefore the most general policy-level dictation of EOL activities. A lot of its content derives from the United Nations' Space Debris Mitigation Guidelines<sup>3</sup>, first created by the UN Committee on the Peaceful Uses of Outer Space in 1999. That document addresses the orbital debris problem via seven guidelines, and in association with the USG ODSPs, is the foundation for NASA orbital debris control documentation such as NASA Procedural Requirement (NPR) 8715.6A<sup>4</sup>, "NASA Procedural Requirements for Limiting Orbital Debris". While the focus of this paper is the implementation

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14. ABSTRACT <b>Recent changes to US space policy regarding the execution of satellite End of Life (EOL) procedures have been driven by the rising significance of the orbital debris problem in Low Earth Orbit (LEO). Therefore current EOL plans are written largely with the aim of reducing long-lasting debris that can linger for decades in the orbit of the defunct satellite. Through an exhaustive discussion of US National, Department of Defense and Air Force Space Command policies for mitigation of orbital debris, this paper details several considerations for writing operational EOL plans, with special applicability to military missions and focus on LEO satellites that are unable to relocate to a graveyard orbit. Further, the recent ungainly re-entry of NASA's Upper Atmosphere Research Satellite (UARS) has highlighted the need to incorporate debris mitigation into the EOL plan after contact has been lost or during re-entry in the interest of public safety. In light of this incident, methods currently used by Air Force Orbital Safety professionals to assess and minimize orbital debris released during and after EOL satellite passivation by accidental explosions, by intentional breakup and due to on-orbit collisions with existing debris are discussed. As integral parts of a holistic EOL plan, re-entry survivability analysis, casualty expectation analysis and intentional breakup activities are also addressed.</b>					
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stemming from Department of Defense Instructions (DoDIs) that arise from the USG Space Policy, the NPRs are also an example of implementation of policy toward orbital debris mitigation.

DoDI 3100.10, “Space Policy”<sup>5</sup> and DoDI 3100.12, “Space Support”<sup>6</sup>, are the primary documents responsible for implementing the USG ODSPs into DoD space operations, just as NPR 8715.6A does for NASA. Section 6.3 of DoDI 3100.12 contains similar language to the ODSPs with regard to release of debris during normal operations. This drills down to the service level via Air Force Instruction AFI 91-217<sup>7</sup>, “Space Safety and Mishap Prevention”. In general, AFIs may be more but not less restrictive than the parent DoDI document. AFI 91-217 contains a lot more detail and addresses a wider slew of case scenarios to ensure implementation.

Similarly, at the Major Command level, these manifest as Air Force Space Command Instruction AFSPCI 10-1204<sup>8</sup>, “Satellite Operations”, and at the unified command level, through US Strategic Command (STRATCOM) Instruction SI 505-4<sup>9</sup>, “Satellite Disposal Procedures”. While Air Force Space Command (AFSPC) is charged with providing and maintaining space capabilities for the joint force military, STRATCOM is one of the nine unified DoD functional commands, and is responsible for providing strategic deterrence and Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) capabilities. STRATCOM and AFSPC therefore work hand-in-hand to enable mainstream DoD space operations. Their guiding policy documents, stemming from national level policy models, seek to re-work the way DoD, USAF and AFSPC conduct operations, towards a more responsible role in lowering the creation of debris in commonly used orbit regimes.

This paper presents the impact and implementation of these national and DoD space policy documents in three phases. Firstly we shall examine the impact of policy on LEO satellite re-entry. Next, we shall examine the implementation piece of USAF EOL passivation activities and associated planning. Finally, other methods adopted from the intent of the National Space Policy Guidelines within the operational Air Force to mitigate the creation of orbital debris at EOL, as well as the concept and importance of “Design for Death” will be discussed.

## **II. Impact of National Policy on LEO Satellite Re-Entry**

We begin with LEO satellite re-entry for an important reason: per the USG ODSPs for Debris Mitigation, satellites in LEO have two options at the end of their mission. If the program should choose to place the satellite in a “storage” orbit to dispose of it, that orbit must have a perigee of above 2000 km and an apogee altitude below 19,700 km<sup>1</sup>. Since LEO can range anywhere from 150 km to 2000 km in altitude<sup>7</sup>, realistically, this is not a goal achievable for a large section of the LEO population, either due to fuel or mission constraints. This is especially true in the case of Research & Development (R&D) satellites that are often single-string, without propellant, or both. Atmospheric re-entry, therefore, is the preferred option for EOL available to most LEO satellites, and this section will discuss the policy burden of that option.

### **A. Satellite Re-Entry within 25 Years**

DoD instructions for space operations attempt to limit the probability of collisions and explosions post-EOL. According to DoDI 3100.12<sup>6</sup> paragraph 6.4, EOL procedures must “leave the satellite in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission”. NASA also has adopted similar policies, namely, NASA Policy Document NPD 8710.3B<sup>10</sup>, “NASA Policy for Limiting Orbital Debris Generation” and NASA Safety Standard NSS 1740.14<sup>11</sup> “Guidelines and Assessment Procedures for Limiting Orbital Debris”. As mentioned previously, AFIs may be more restrictive than DoDIs, and the USAF imposes an additional requirement of re-entry no more than 30 years after launch for LEO vehicles, atmospheric re-entry notwithstanding<sup>7</sup>. It also further restricts the apogee of LEO orbits to 18,400 km, vice the 19,700 km recommended by the USG ODSPs.

The End of Mission plan reviewed by the Program Manager and the AFSPC Office of Safety needs to document compliance with this and all other regulations discussed. For maneuverable satellites, while this plan must allow Orbit Analysts (OAs) leeway to adjust burn times and orbital positions according to operational needs or ground station contact times, it must still provide sufficient detail to prove the capability to re-enter within 25 years. For non-maneuverable satellites, this can be more of an issue. LEO satellites with perigee altitudes greater than 700 km are unlikely to re-enter within 25 years naturally, using conservative projections for solar weather; therefore, if they have none or insufficient propellant to stage a controlled re-entry, they are unlikely to ever get the green light to launch via the DoD.

This altitude “restriction” is a significant limiting factor for low budget, R&D-mission satellites. While the USG guidelines leave some measure of leniency to orbital debris mitigation for “cost efficiency” considerations, AFI 91-217 specifically calls out that *all* Air Force space systems, including R&D systems, must comply with their

requirements and similar ones imposed by STRATCOM<sup>9</sup>, leaving only the tenuous safety waiver process as a possible way forward for non-compliant low-budget systems.

## **B. Re-Entry Survivability Analysis and Casualty Expectation**

Even after space vehicle breakup in the upper atmosphere during re-entry, certain component parts made out of tungsten, titanium, stainless steel, beryllium or carbon-carbon may not reach their melting point by aero heating. In many cases these components survive re-entry, which has led to the study of “casualty area”. The recent ungainly entry of NASA’s Upper Atmosphere Research Satellite (UARS) was a stark highlight of the public significance this area can take on. A measure of satellite survivability during uncontrolled entry and break-up, casualty area is defined as the area around a debris impact point within which a person present will become a casualty\*.

NASA has chosen to exercise control over casualty expectation through casualty area. NASA Safety Standard NSS 1740.14<sup>11</sup> Section 7 narrows the maximum casualty area permissible for a re-entering body to 8 m<sup>2</sup>. DoDIs do not mention a limit for casualty area, focusing instead on “casualty expectation”. This is defined as the average number of casualties that can occur as a result of a re-entry event if the event were to be repeated thousands of times. DoDI 3100.12<sup>6</sup> sets the maximum casualty expectation at no greater than 1 in 10,000. Neither DoDIs nor NSSs require a controlled re-entry to guarantee that it will avoid inhabited areas, unless the casualty expectation is above this limit. At that point the satellite will be required to budget propellant for a final entry maneuver that will steepen the flight path angle and allow for Earth-impact at a selected longitude and latitude, most likely in the Pacific Ocean. Therefore, *a military or military-affiliated non-maneuverable satellite must, from design inception, meet these casualty expectation criteria*; another example of increasing regulatory demand on satellites designed on low budgets with no propulsion.

An example of the divergence between the NASA and DoD casualty expectation standards are the Air Force standard Delta launches. Delta II second stages, for example<sup>12</sup>, have a casualty area of 10.8 m<sup>2</sup>. However, as DoDIs only enforce a maximum casualty expectation instead of casualty area, Delta II and Delta IV vehicles do not have to comply with NSS 1740.14. Further, if the body has the ability to control its own re-entry and can do so over a non-populated or ocean area, even the casualty expectation of less than 1 in 10,000 may be waived. Therefore, after releasing their payload to LEO, these Delta motors can reignite their own second stages and stage a controlled re-entry over the Pacific Ocean.

Every component piece of the re-entering spacecraft bus and payload must be modeled to determine its ablation temperature, demise altitude (measure of survivability) and casualty area. An example of this analysis can be found in the literature<sup>13</sup>. From this, a picture of surviving pieces can be drawn.

The distribution of population can be plotted against orbital inclination by year. When this population density number is multiplied by the summed casualty area of all re-entering parts, the total casualty expectation for random re-entry during a particular year can be calculated as:

$$\text{Expected Casualty} = \text{Casualty area (m}^2\text{)} * \text{Population density (1/m}^2\text{)} \quad (1)$$

There are several approved software packages that can calculate measures of survivability based on various criteria: Object Re-entry Survival Analysis Tool (ORSAT), Spacecraft Atmospheric Re-Entry and Aero-thermal Breakup (SCARAB), Spacecraft Entry Survival Analysis Module (SESAM) and NASA’s Debris Assessment Software (DAS) are some of these. Lips<sup>14</sup> performs an excellent comparison of the fidelity and results of these various tools.

## **III. Impact of National Policy on EOL Passivation**

As discussed earlier, standard practices for orbital debris mitigation in LEO dictate relocation to an often unachievable orbit. Satellites are therefore commonly decommissioned in orbits that will ensure de-orbit due to atmospheric drag. Satellites can remain for a long time in this adverse environment where collisions with space debris or meteoroids and the high temperature changes (thermal cycling) between sunlit passages and eclipses could exert stresses sufficient to trigger a break-up.

The largest percentage of catalogued space debris population can be traced to the fragmentation of spacecraft and launch vehicle orbital stages<sup>2,3</sup>. The majority of these breakups were unintentional, many arising from the abandonment of spacecraft and launch vehicle orbital stages with significant amounts of stored energy. Therefore, debris mitigation after contact has been lost or during re-entry must be actively considered as part of an EOL plan.

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\* From [http://www.space.gov.au/SpaceLicensingSafetyOffice/Documents/FSC\\_Pubn1\\_20050602105043.pdf](http://www.space.gov.au/SpaceLicensingSafetyOffice/Documents/FSC_Pubn1_20050602105043.pdf)

The most effective method of mitigation is passivation, which requires the removal of all forms of stored energy, including residual propellants and compressed fluids and the discharge of electrical storage devices. This is specifically called out in the USG ODSPs, under the objective of minimizing debris caused by accidental explosions. Section 2.2 directly states that all on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when no longer required<sup>1,2</sup>, dictating that the impact of an unavoidable subsequent explosion be reduced however possible.

Therefore, we shall discuss the implementation of this policy directive via passivation. However, passivation is a design process. If not carefully considered, the satellite could still be at a reasonably high energy state. We shall address this issue in three parts – pre-passivation planning, which can be highly dependent upon the components on-board; the passivation checklist process and concerns to address while designing that process, as well as the post-passivation concerns raised by the USG ODSPs.

#### **A. Pre-Passivation – Planning EOL around Spacecraft Components**

The components onboard a spacecraft have a large role in determining the level of detail that must go into EOL planning. As discussed, one of the primary drivers is minimizing the destructive capability of satellite components after contact with the parent vehicle is no longer possible. The large amount of debris floating in LEO makes impact with the satellite at some later point in its 25-year orbit almost inevitable. A collision that produces an explosion due to the satellite being in a high-energy state can create thousands of debris particles that will linger in the orbit of the erstwhile satellite and become a hazard to future missions.

Therefore every stored energy source must be deactivated or dissipated to the maximum extent. Today, if any of the following components are present aboard the spacecraft, mitigation measures should be addressed as part of the EOL plan<sup>13</sup>.

1. *Fluids.* Fluid and thermal management issues aboard the spacecraft must be addressed. Cryogenic liquids, in particular, have been widely used aboard scientific missions, and are stored in various hazardous states. Some examples include high-pressure Joule-Thomson expansion devices for cooling of infrared or hyperspectral detectors, or storage of super-critical low-pressure helium to provide oxygen and nitrogen for manned missions<sup>15</sup>. The design for cryo-coolers on a short-term mission may be different from those on, say, the International Space Station, and the means by which these devices will be safed or jettisoned must be addressed accordingly.

2. *Propellant.* Every maneuverable satellite should have a  $\Delta V$  budget dedicated exclusively to EOL operations. Once a degenerating or disposal EOL orbit has been achieved, fuel onboard must be jettisoned to the maximum possible extent. For example, CloudSat, a NASA Earth Science Pathfinder mission launched in 2006, uses a diaphragm that will aid in expulsion of remaining hydrazine fuel; however approximately 0.5 kilograms will remain trapped between the fuel tank's inner wall and diaphragm<sup>16</sup>. To mitigate this, the satellite was designed with latch valves that will close, in addition to the thruster valves, to prevent excess hydrazine from escaping. In the event that design does not permit such mitigation, further perigee lowering maneuvers are an excellent way to burn off excess fuel and fulfill the DoD burn-in requirement.

3. *Pyrotechnic Devices.* Spacecraft utilize pyro or firing circuits for functions such as severable bolts to jettison parts, operation of certain actuator valves, extending appendages from their storage compartments, etc<sup>15</sup>. Procedures to disconnect or safe the charging bank of capacitors should be included in the EOL plan to prevent accidental discharge of these devices.

4. *Radioactive Material.* Depending on the mission, a spacecraft could carry radioactive materials onboard for purposes such as instrument calibration, as a heat or power source, as structural members or as part of a space experimental payload<sup>17</sup>. A satellite with radioactive material would likely have to be designed with enough fuel to reach a disposal orbit, due to the possibility of that material surviving re-entry and being distributed into the atmosphere. Various US and international regulations, to include the International Atomic Energy Agency (IAEA) Safety Series #6, "Regulations for the safe transport of radioactive material"<sup>18</sup> would govern this decision and compliance would have to be captured in the EOL plan.

5. *Power Design.* The power system onboard the spacecraft, with special reference to the batteries, are the most common source of stored energy left onboard. Most spacecraft have fault protection logic built into their automatic tasking engines (ATEs) to prevent them from being accidentally commanded off or from being discharged beyond a certain critical level. If such logic exists it may not be possible to dissipate battery energy as easily. Depending on

the satellite configuration, indirect methods to bring the power to the lowest possible configuration should be carefully addressed.

## **B. Passivation Sequence**

The following general checklist for passivation of a satellite will also be highly dependent on the spacecraft's components and design<sup>13</sup>.

*1. Start of EOL procedures.* Firstly, as described above, stored energy sources must be identified and measures to minimize or dissipate should be well drawn out. Any gas or liquid filled batteries, pressurized systems, propellant lines and tanks (regardless of tank design) and control moment gyroscopes must be depleted. In addition, range safety systems must be deactivated.

An example is the AFSPC operational asset TacSat-3. At EOL, this vehicle will have two stored energy sources; the reaction wheels and the charge in the battery<sup>19</sup>. By design, Mission Engineers (MEs) have the ability to override all fault protection and autonomy imposed by the ATE. Therefore the plan for passivation for TacSat-3 will involve disabling the Peak Power Trackers and ensuring they do not enter bypass mode. This will prevent the batteries from charging when the solar arrays are exposed to the sun, instead drawing power from them and allowing the momentum wheels to spin down.

*2. Turning off non-essential equipment.* All non-essential equipment such as GPS, Star Trackers, Inertial Reference Units (IRU), back-up power, wide-band transmitters, Attitude Determination Control Systems (ADCS), etc., should be permanently turned off. For classification sensitive payloads, appropriate measures to ensure that no one else can command the satellite once the DoD has ceased control must be documented.

Payloads can be left on for a period to accelerate discharging of the battery, but should be turned off before an under-voltage trip occurs. However, sensitive payloads remaining active as the satellite's state of health degenerates may not be an attractive risk. In such cases, battery discharge may be accelerated by slewing the spacecraft to an anti-sun attitude. It should be noted, however, that when the Guidance, Navigation and Control (GN&C) system is placed on standby (non-operational), atmospheric torques may cause the satellite to tumble, possibly lengthening the time for discharge. All these issues, as pertinent to the satellite at hand, should be carefully balanced to ensure the minimum possible energy configuration.

*3. Making the spacecraft inert.* Once all measures to dissipate stored energy aboard the satellite are complete and only those systems needed to complete EOL commanding are on-line, the spacecraft is considered decommissioned. It will be at the lowest possible energy state and un-commandable except for the time-tagged EOL command block uploaded to the Spacecraft Computer (SCC) that will turn the satellite into a non-functional piece of space debris. This will complete the passivation sequence.

## **C. Post-Passivation: Debris released by accidental explosions**

Especially once the spacecraft is beyond commanding, the potential for accidental explosions due to thruster malfunctions, tank failures due to small debris impact, battery ruptures, structural degradation or accidentally induced high rotation rates<sup>20</sup> can be high. As was the case with UARS, if the satellite is approaching burn-in, spacecraft breakup could occur during the final orbit. Therefore a crucial part of reducing the orbital safety hazard is capturing and quantifying these probabilities in an EOL plan, if they exist.

If a spacecraft contains any of the systems listed below, the EOL plan must incorporate a formal Failure Mode and Effects Analysis (FMEA). This analysis should be conducted as part of pre-launch readiness approvals, and updated prior to EOL<sup>13</sup>.

*1. Range safety.* Though many consider the space shuttle's Solid Rocket Booster (SRB) range safety to be the only publicly necessary mechanism, to prevent civilian casualties in the event of a deviated launch trajectory, such a picture is overly simplistic. Military launches are a large percentage of space activity, and the cutting-edge sensitive technology they carry onboard can be highly desirable to foreign nations. When executed properly, a range safety system can be designed to minimize orbital debris; however it is estimated that nearly 20% of all spacecraft breakups may be attributed to the unintentional detonation of on-board self-destruct or range-safety systems<sup>20</sup>.

*2. Hydraulic systems.* Hydraulic cylinders, drive systems or motors find use in propulsion systems, gimbal servo actuators, Thrust Vector Control (TVC) systems and in power systems similar to the Hydraulic Power Units (HPUs) on the erstwhile space shuttle's SRBs. Such systems typically have a variety of pressurized moving parts such as

fuel supply modules, hydraulic reservoirs and fluid manifold assemblies, and can present a significant hazard that must be addressed as part of EOL planning.

3. *Acoustic generators.* Thermo-acoustic generators are used in space to convert heat to electricity using sound-based generators. In addition, piezoelectric acoustic generators are lightweight and free from RF noise, and find a variety of applications in satellite microprocessors and amplification or oscillation type circuits<sup>\*\*</sup>. Another example application is onboard the *Cassini* spacecraft, to reduce the acoustic environment at the mountings for the three onboard radioisotope thermoelectric generators (RTGs)<sup>21</sup>.

The FMEA's Risk Priority Numbers (RPNs) can highlight the areas of greatest concern for accidental explosions, and should be used to justify any recommended passivation decisions. Excluding the case of on-orbit collisions, which is discussed in section IV, AFI 91-217 now requires that the integrated probability of explosion be less than 0.001 for all USAF launches<sup>7</sup>. The FMEA is therefore a required tool to calculate the failure modes of each spacecraft, probability of failure and integrated probability of explosion to comply with USAF and AFSPC regulations.

#### IV. Other Methods Used to Mitigate Orbital Debris at EOL

Lastly, whenever examining orbital debris mitigation, we must touch on intentional breakup activities and the probability of on-orbit collisions after EOL has been conducted. The latter has a clear relationship to the disposal orbit in which the satellite is left, and how quickly that orbit is decaying into the atmosphere with time. The former is trickier in light of the obvious military utility that must, at times, be exercised to keep sensitive technology out of non-allied hands. The USG ODSPs deal with this vaguely, stating that every instance of planned release of debris larger than 5 mm in any dimension that might violate the 25-year re-entry requirement should be "evaluated and justified on the basis of cost effectiveness and mission requirements"<sup>1,2</sup>. The *cost-effective* term is relevant to relatively cheap technology demonstrator missions such as cubesats, wherein it may not be feasible to add propellant in light of the mission budget. The *mission requirements* term hints at intentional breakup activities, which are discussed in this section.

##### A. Intentional breakup activities

Examples of intentional space vehicle breakup debris include jettisoning frangible bolts or using pyrotechnic devices to separate the spacecraft from its payload or other component parts. Intentional breakup has also been executed as part of structural testing, destroying classified equipment aboard military satellites to prevent recovery by non-allied nations, space-borne explosive testing and in Anti-Satellite (ASAT) and other space weaponization testing<sup>12</sup>.

However, there are several considerations to executing an intentional explosion or collision. The growing concern over the space debris problem and its impact on current space operations has led to the DoD clamping down on such intentional debris creation activities. An excellent example of space operation impact is China's recent destruction of its Fengyun-1C weather satellite with an ASAT device. Now widely viewed as the most severe fragmentation in 50 years of space operations, NASA estimates that the breakup of Fengyun caused over 950 pieces of space debris with a size of greater than 10 centimeters; each with a velocity in excess of 12 km/sec, spanning 200 to 3,800 kilometers above the surface of the Earth<sup>22</sup>.

Current National Space Policy dictates that any intentional breakup plans must be approved on a case-by-case basis by the Secretary of Defense<sup>2</sup>. In addition, the USAF requires that before any intentional breakup activities can be conducted, it must be conclusively proven that for 24 hours after the break-up, the probability of resulting debris larger than 1 mm impacting any operating spacecraft is no greater than one in a million (probability of  $10^{-6}$ )<sup>7</sup>.

##### B. On-orbit collisions after EOL

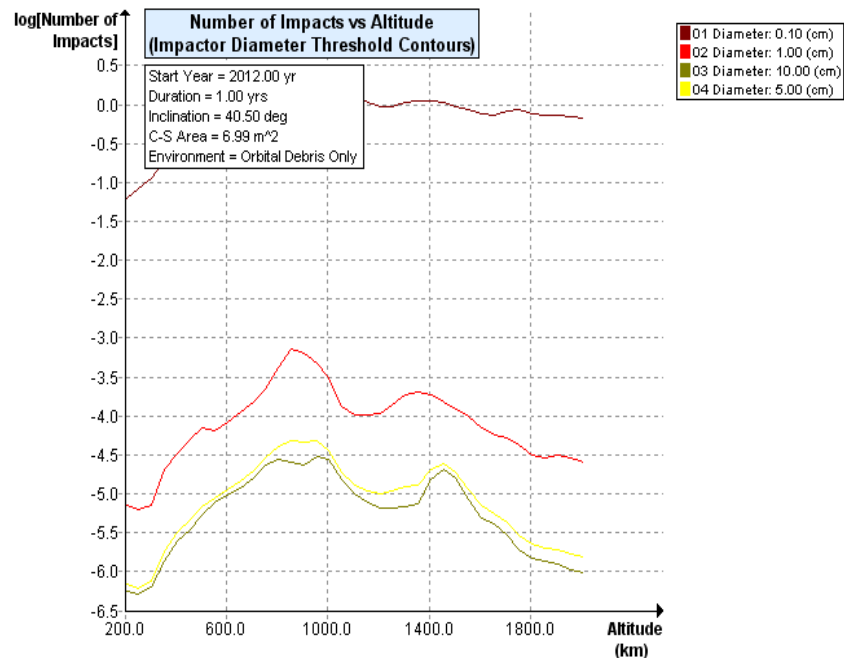
Two categories of on-orbit collisions must be considered: vulnerability to space objects smaller than 10 cm in diameter and to objects larger than 10 cm at the orbit altitude of the satellite. It is generally accepted<sup>7</sup> that objects larger than 10 cm can cause catastrophic damage to a satellite. The objective is for maneuverable satellites to determine if the current altitude is the most optimal for executing EOL, taking the debris and potential for post-EOL collisions at that altitude into consideration.

Fig 1 below shows example curves for the number of predicated impacts vs. altitude<sup>13, 19</sup> across four sizes of orbital debris – 1 mm, 1 cm, 5 cm and 10 cm. The analysis shown in Fig 1 was performed using DAS, and spans a

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<sup>\*\*</sup> From "Kyocera Piezoelectric Acoustic Generators" - <http://www.avx.com/docs/masterpubs/piezo.pdf>

timeframe between 2012 and 2013. This is in fact a conservative analysis. Lips<sup>14</sup> points out that DAS assumes higher heat capacities and emissivity than SCARAB and ORSAT, possibly artificially increasing the survivability of re-entering parts.



**Figure 1. Impactor Diameter Threshold Contours**

## V. Conclusion: Design for Death

The problem of orbital debris is not a fringe problem anymore. As this paper attempted to show, there is enough regulation to ensure that all agencies and personnel involved in space operations are aware of the problem. Therefore, as responsible stewards of space, it remains our responsibility to “design for death”, i.e., to make sure that the designs of spacecraft, launch vehicles and missions that are upcoming have taken into consideration the orbital debris problem and have a mitigation strategy in place to minimize adding to the problem. The trend of EOL considerations (such as out of compliance casualty expectation or re-entry projections) coming to light only after the Critical Design Review (CDR), at which point it is not cost-effective to design mitigations in, should be avoided as much as possible. The objective of all these standards is to emphasize the concept of “design for death”, i.e., designing future satellites with an eye on its end of mission.

Satellite EOL planning is an exhaustive process that incorporates many elements, many of which have links to the initial design process of the satellite. In addition, considering the problem of orbital debris during and after execution of EOL will require foresight and planning, as well as adherence to guidance and instructions put in place by NASA and/or the Department of Defense.

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## **Appendix A**

### **Acronym List**

ADCS	Attitude Determination and Control System
AFSPC	Air Force Space Command
ASAT	Anti Satellite
ATE	Automated Tasking Engine
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance
DAS	Debris Assessment Software
DOD	Department of Defense
EOL	End of Life
FMEA	Failure Mode and Effects Analysis
GN&C	Guidance Navigation and Control
GPS	Global Positioning System
HPU	Hydraulic Power Unit
IAEA	International Atomic Energy Agency
IRU	Inertial Reference Unit
LEO	Low Earth Orbit
ME	Mission Engineer
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirement
NSS	NASA Safety Standard
ODSP	Orbital Debris Mitigation Standard Practices
ORSAT	Object Reentry Survival Analysis Tool
RPN	Risk Priority Number
RTG	Radioisotope Thermoelectric Generators
SCARAB	Spacecraft Atmospheric Reentry and Aerothermal Breakup
SCC	Spacecraft Computer
SESAM	Spacecraft Entry Survival Analysis Module
STRATCOM	Strategic Command
TVC	Thrust Vector Control
UARS	Upper Atmospheric Research Satellite
USAF	United States Air Force
USG	United States Government

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